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ACOUSTIC DETECTION FROM AERIAL BALLOON PLATFORM

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ABSTRACT

The US Army Research Laboratory (ARL) and US Army Night Vision and Electronic Sensors Directorate (NVESD) are leading the research and development in autonomous sensing and sensor networks for the Networked Sensors for the Future Force (NSfFF) and Future Combat System (FCS). With the emphasis being shifted to lighter and more mobile forces, ARL and NVESD have been collaborating and exploring various mobile platforms such as robotic vehicles and aerial platforms such as unmanned aerial vehicles (UAVs) and balloons. Our most immediate collaboration focuses on the use of acoustic sensors on small balloons and/or aerostats at several elevations and on the ground with the primary goals of: (i) investigate the acoustic sensing and detection ranges; (ii) acoustically cue IR imagers and/or video cameras; and (iii) explore the networking of elevated sensors and ground sensors for NSfFF. In this paper, we only focus on the first goal, the acoustic detection portion of the collaborative effort.

1. INTRODUCTION

Acoustic sensors are being pursued by the Army as part of multi-sensor solutions to networked, distributed, unattended ground sensing. NSfFF ATD and Disposable Sensors are Army Science & Technology Objectives that are pursuing acoustic sensors for unattended ground sensing and cuers for the more expensive and less ubiquitous imagers. Thus, acoustic sensors play a potential key role in situational awareness and addressing critical FCS Unit of Action ORD requirements and Field Operational Capabilities.

Acoustic sensors have many advantages that include non-line-of-sight, omni-directionality, passive, low-cost, and low-power, weight, and size. Acoustic sensors are the primary sensors for most (if not all) Unattended Ground Sensor (UGS) systems because they can provide detection, direction finding, classification, tracking, and accurate cueing of other high-resolution sensors [1]. They are equally effective against continuous sources such as helicopters, tanks, SUV's, generators and other tactical vehicles [2-3], and transient events from indirect and direct fire such as mortars, rockets, artillery, and snipers [4-5]. However, acoustic sensing is highly dependent on the environmental conditions. For ground-based acoustic sensors, acoustic attenuation is due to the atmospheric conditions (e.g., temperature, wind speed and wind direction) in addition to ground impedance, vegetation and other terrain features [6]. By elevating the acoustic sensor arrays, via balloon to the point where the sources on the ground are essentially line-of-sight, propagation losses due to the ground are mitigated. With an on-board GPS sensor, inclinometer and digital compass, precision knowledge of the balloon and the acoustic sensor array's position and orientation are known at all times. With one elevated array, a 3-dimensional localization solution for a detected acoustic event can be obtained via the intersection of the globally-mapped vector solution and the ground. Furthermore, if IR imagers and visible cameras mounted on a pan/tilt unit are present on the balloon, they can be directed to the acoustically derived solution to validate the detected event. In contrast, localization via triangulation between multiple dispersed UGS's with collocated imaging sensors would not have direct line-of-sight to the target's location.

The research discussed in this paper pursues the quantification of the performance benefit to acoustic sensing from elevation above the ground terrain limitations.

2. ACOUSTIC PROPAGATION MODELS

Using acoustic and propagation models from the Acoustic Battlefield Decision Aid (ABFA) tool, we can predict the acoustic detection performances at different

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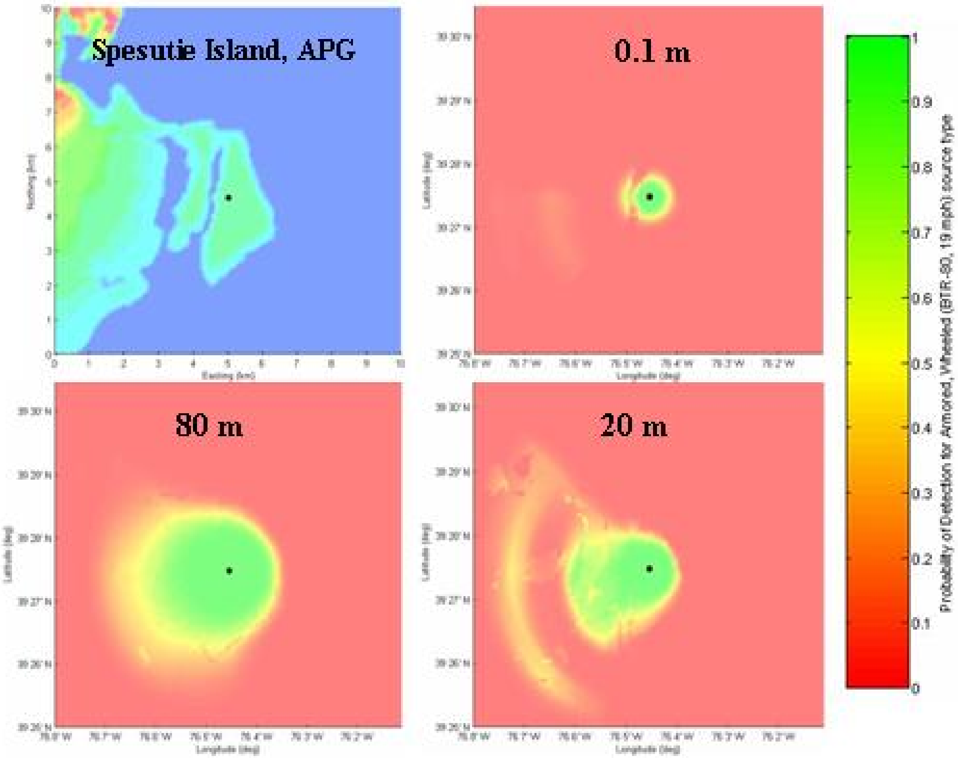
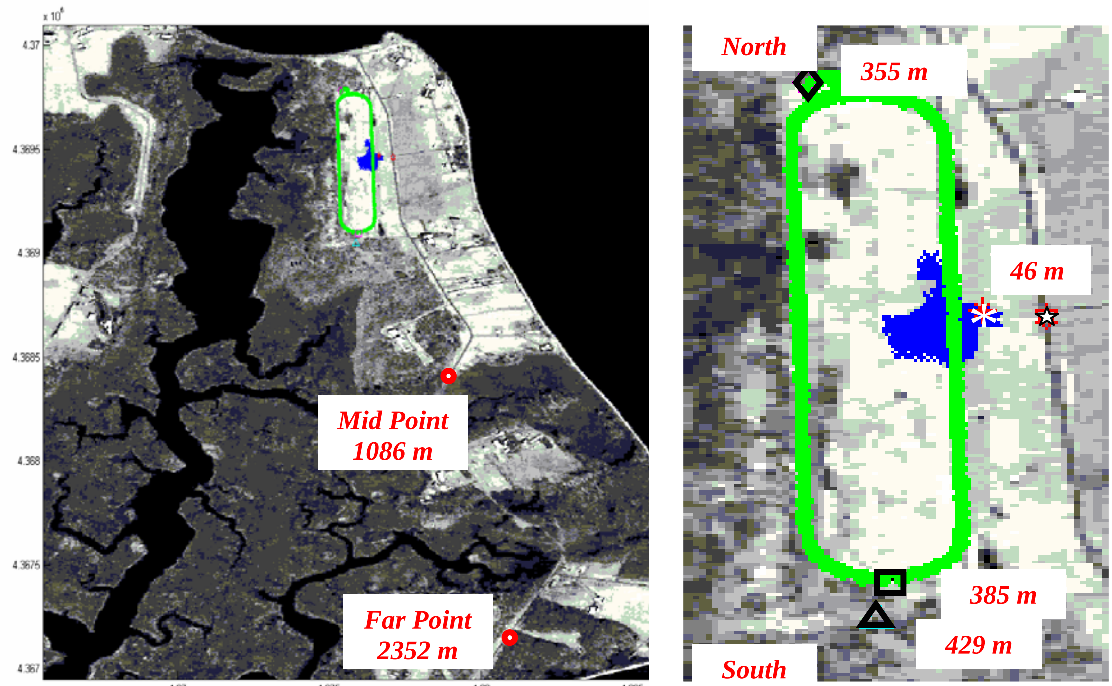


Fig. 1: *Predicted detection results for a 100 Hz signal from ABFA for acoustic sensors on the ground (0.1m) and at 20 m and 80 m elevations using 8 am, 24 June 2004 MET data Spesutie Island, APG.*



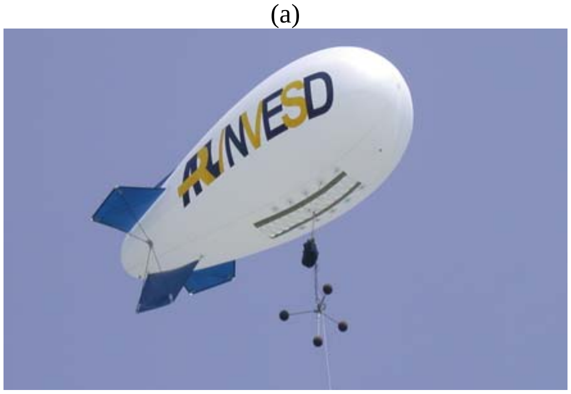
(a) (b)

Fig. 2: (a) *Spesutie Island test area with the far and mid locations (red circles) marked along the road that was traveled by the intended test vehicles and unintended traffic.* (b) *The test track is the rectangular shape (green) and the balloon track locations are the blue shaded region (right center area overlaying the test track). The asterisk marks the location of the ground array (reference location), the star marks the pole by the road 46 m from the array, the square and triangle (located adjacent to the track 385 m and in the woods at 429 m from the array respectively) mark the location of the cannon shots at the south end and the diamond (located 335 m from the array) marks the cannon shots at the north end.*

elevations and on the ground under a variety of atmospheric conditions [7]. Fig. 1 shows the predicted detection ranges for a 100 Hz signal at different altitudes from ABFA for a specific time of day at a specific location, e.g., 8 am on 24 June 2004 at Spesutie Island, Aberdeen Proving Ground (APG) (aerial map shown on the left in Fig. 2). Actual meteorological (MET) data were used as input into ABFA to generate these results. In this example, where we have upward diffraction due to the temperatures being cooler at higher altitudes, we can definitely observe an increase in detection ranges at elevated heights. Specifically, the detection range is approximately twice at 20 m and approximately four times at 80 m elevation respectively compared to the detection range at 0.1 m above the ground.

3. FIELD EXPERIMENTS

(a)



(b)

Fig. 3: (a) *The 1 m spacing tetrahedral ground array mounted on a tripod and* (b) *the 55 cm spacing tetrahedral acoustic array mounted on a 20 ft size balloon*

In this paper, we discuss the preliminary field experiments conducted by ARL and NVESD at Spesutie Island, APG in late August 2004. Two acoustic sensor array configurations were used for the data collection: (i) a 4-element tetrahedral array with 1 m arms mounted on a tripod approximately 1 m off the ground (referred to as the "ground acoustic array") shown in Fig. 3 (a) and (ii) a 4-element tetrahedral array with 55 cm arms mounted on a 6.1 m (20 ft) balloon elevated at height up to approximately 152 m (500 ft) (referred to as the "balloon acoustic array") shown in Fig. 3 (b).

We collected acoustic signatures of impulsive blasts generated by a propane canon and two ground vehicles maneuvering around the test track shown in Fig. 2. The propane cannon was operated at fixed locations while the balloon was at a fixed maximum elevation of 152 m (500 ft) and also at varying elevations. Attempts were made to keep accurate associated times, ground truth positions via GPS and position markers and as well as MET data.

3.1. Test Measurement Description

The same types of microphones, amplifiers, and data acquisition systems were used for the balloon and ground sensor arrays with identical settings. Only the baseline of the arrays were different with the balloon baseline decreased to 55 cm to lower the balloon payload to < 6.8 kg (15 lbs) limit. Laboratory grade ACO Pacific microphones were attached inside aluminum tubing with the microphone exposed and the cabling passed to the center of the array through the tube arms. The microphone power supplies were set to 40 dB gains resulting in outputs of ~1.8 ± 0.3 V/Pa. The data was recorded on battery-powered Ref Tek 130 data recorders with zero gain at 1 kHz and 24 bit resolution. The Ref Tek time on the balloon was synchronized to GPS time while the GPS sensor was directly connected to ground system.

The balloon system shown in Fig. 3 (b) required several additional pieces of equipment to provide accurate location and orientation information. A Garmin Etrex Vista GPS handheld unit was used to record the balloon positions at 2 s intervals and placed in the equipment bag on top for maximum reception. A True North Revolution compass module was mounted on the "zero-degree" arm and the companion PDA was used to record compass readings, roll, and pitch every 2 s and also placed in the equipment bag along with the Ref Tek recorder, two NiMH 6 V, and two microphone power supplies. The equipment bag was attached to the balloon and the array was hung on a rope approximately 1.2 m below the balloon.

The test vehicles were equipped with GPS units but they did not work properly. However, ground truths were recorded by hand at specific test location markers on and around the test track.

3.2. Test Event Description

The two light vehicles used were a HMMWV and a Jeep Tahoe. The track and roads used during the test are shown in Fig. 2. The initial sequence of test runs did not include the propane cannon blasts because of range clearance problems. The balloon was positioned at an elevation of approximately 152 m. The HMMWV was driven around the 1.6 km track twice. The first lap was driven at 48 kph (30 mph) and the second lap was driven at 32 kph (20 mph). The Tahoe performed the same test sequence with the exception that the horn was sounded multiple times at the north and south ends of the track. The Tahoe also drove to the main road and south to the far location while sounding the horn periodically.

In the second sequence of test runs, a propane cannon was mounted in the back of the HMMWV on the open flat-bed area of the vehicle. The HMMWV was driven around the track twice and while stopping at the north and south ends to fire 10 shots with the propane cannon. The balloon was fixed at 152 m elevation.

In the third sequence of test runs, the HMMWV was driven to a location just past the south end of the track in a stand of trees (429 m from ground array) and the cannon was fired while the balloon was being lowered to the ground. The balloon was then raised to 152 m at 15.2 m (50 ft) increments starting at 30.4 m (100 ft) while the propane cannon was fired from the stand of trees. The HMMWV then proceeded to the far location and the cannon was fired while the balloon was being lower again by 15.2 m increments. At approximately 91.4 m, the cannon was moved to the mid point (1086 m from ground array) because of a lack of radio communication contact with the cannon firing team. The balloon was raised back to 152 m and lowered in 30.4 m increments to 60.8 m and then in 15.2 m increments to 152 m elevation. This last test sequence completed the planned test events for the field experiments.

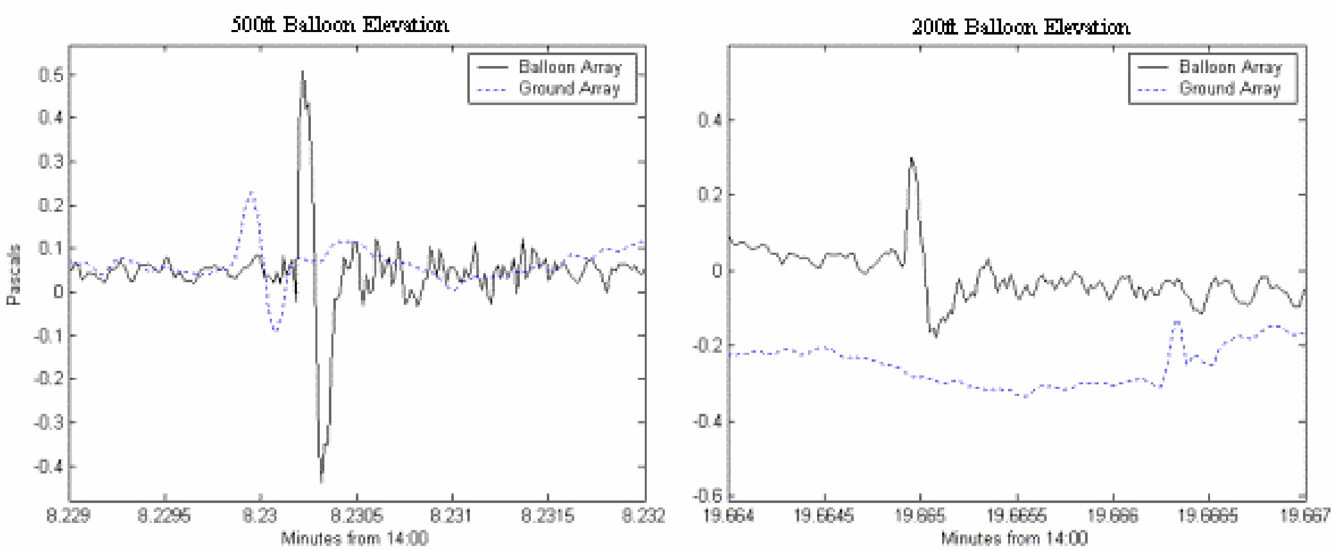
During the test, nearby road traffic and other sounds in the background were noted with the corresponding times. Some of these signatures prove to be valuable in the subsequent data analysis.

4. DATA ANALYSIS AND RESULTS

In this paper, we present acoustic detection results derived from preliminary (qualitative) analysis of the acoustic data from the center microphones of the two arrays. The acoustic array data and auxiliary data (e.g., MET data) from the recent August field experiment are in the process of being downloaded and processed and will be reported in future papers and/or technical reports. We select several interesting impulsive and continuous acoustic events/sources from the sequences of test runs described in Sec. 3.2 to highlight the detection capabilities of the balloon acoustic array vs. the ground acoustic array. The results comparing signal and energy levels are shown below in Fig. 4 to Fig. 8.

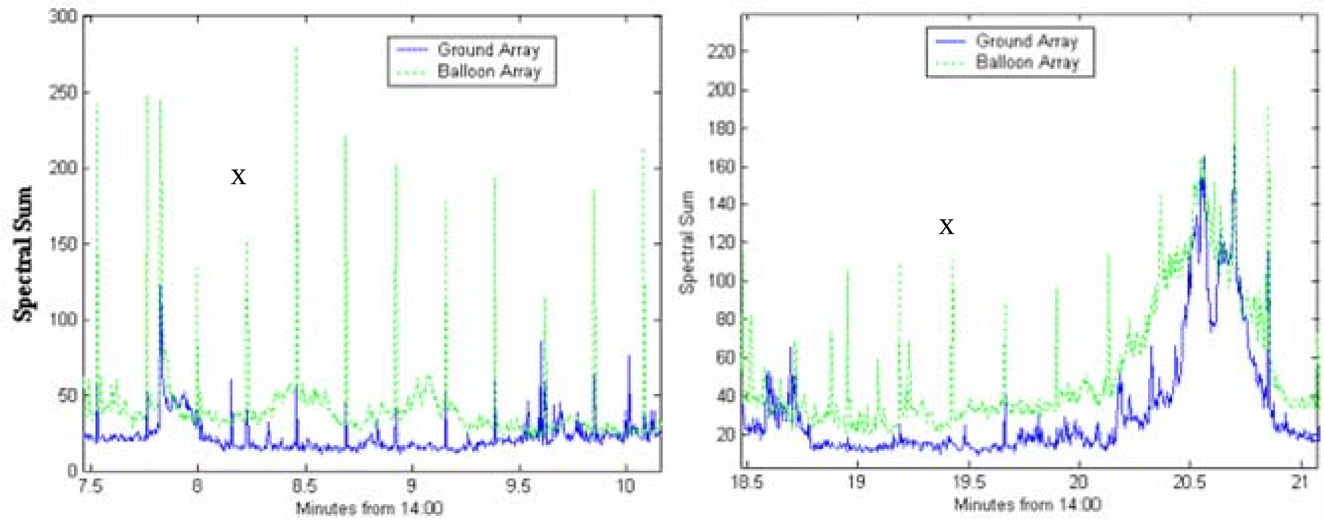
4.1. Impulse Detection Analysis

For the transient impulse analysis, we use signal amplitudes (with appropriate calibration adjustments) in the time domain and frequency domain via spectral sum to compare and contrast the signals received from the ground and balloon acoustic arrays. The spectral sum is the sum of all broadband energy from 0–500 Hz over ½-second window data and it gives an indication how much of the impulsive signal energy is being detected by the sensors.



(a) (b)

Fig. 4: *Amplitude vs. time plots for one of the propane cannon shots as detected by the center microphones of the ground acoustic array (blue dashed line) and the balloon acoustic array (black solid line) at* (a) *152 m (500 ft) and* (b) *45.6 m (150 ft) elevations respectively. The distance from the propane cannon to the ground acoustic array is 1086 m.*



(a) (b)

Fig. 5: *Spectral sum vs. time for a series of propane cannon shots from center microphones of the ground acoustic array (blue solid line) and the balloon acoustic array green dashed-line) at* (a) *152 m (500 ft) and* (b) *60.8 m (200 ft) elevations respectively. The x's mark the corresponding isolated shots shown in Fig. 4.*

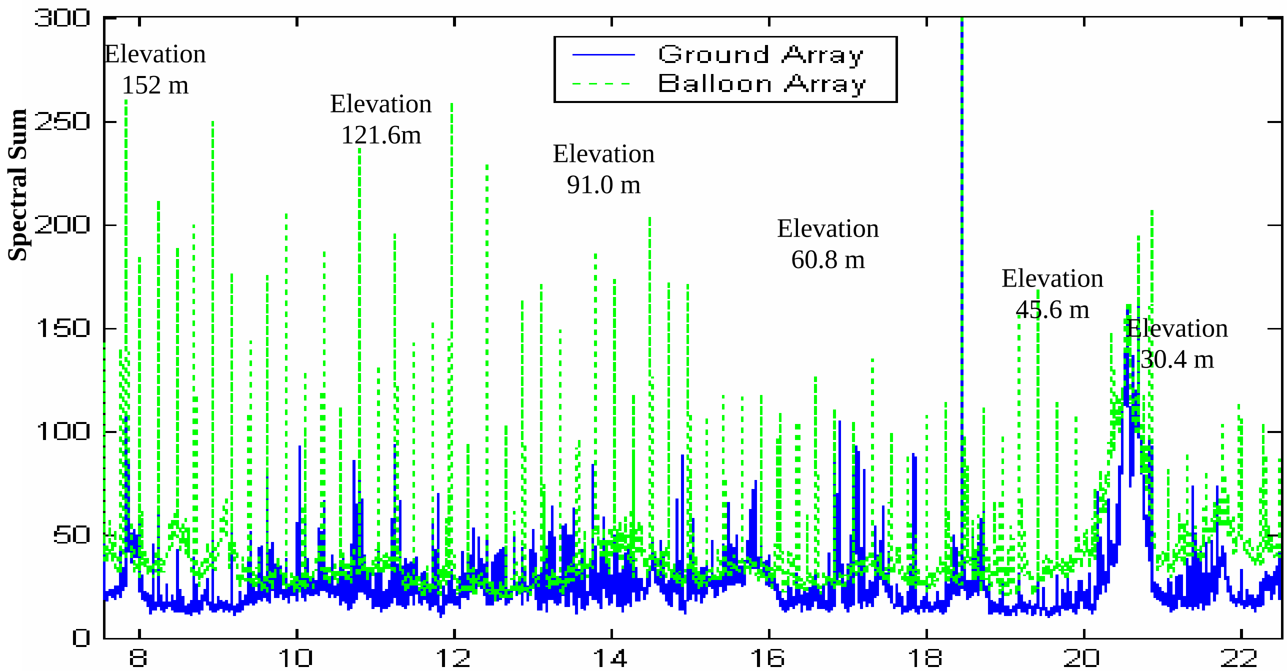


Fig. 6: *Spectral sum vs. time for a long series of propane cannon shots as detected by the ground acoustic array (blue solid line) and the balloon acoustic array green dashed-line while the balloon elevation was lowered from 152 m to 30.4 m..*

Fig. 4 shows amplitude vs. time plots for one representative propane cannon shots as detected by the ground acoustic array (blue dashed line) and the balloon acoustic array (black solid line) at (a) 152 m (500 ft) and (b) 45.6 m (150 ft) elevations respectively. The distance from the propane cannon to the ground acoustic array is approximately 1086 m. Both plots clearly show improved signal level detection by the elevated balloon sensors (e.g., a gain factor of ~ 2 at 60.8 m and a gain factor of ~ 4 at 152 m respectively).

Fig. 5 shows the spectral sum vs. time for a series of propane cannon shots as detected by the ground acoustic array (blue solid line) and the balloon acoustic array (green dashed-line) at (a) 152 m and (b) 45.6 m elevations respectively (Note that the x's in Fig. 5 indicate the corresponding isolated shots shown in Fig. 4). The plots clearly shows increased detection signal levels for elevated balloon array compare to the ground array for all the shots fired. Ideally the spectral sum for all the shots detected by the ground arrays should be similar because the shots were fired at a fixed location.

However, the signal levels varied (actually decreasing slightly) over the observed time window (i.e., 2.5 min) possibly due to the changing atmospheric conditions, variations in sound pressure level of shot to shot, and/or changing ambient noise from unexpected sources. A more detailed analysis with beamforming and noise equalization will be done to isolate the signals of interest.

Fig. 6 shows the spectral sum vs. time for a long series of propane cannon shots as detected by the ground acoustic array (blue solid line) and the balloon acoustic array green dashed-line while the balloon elevation was lowered from 152 m to 30.4 m at 15.2 m increments. From the plot, for these series of transient events, we can see the clear benefit of increasing the altitude of the sensor to improve the signal levels.

4.2. Continuous Wave Detection Analysis

For continuous wave detection analysis, we focus on the acoustic signatures of the HMMWV (intended source) as it moves around the test track shown in Fig. 2. The lack of GPS ground truth was remedied by the use of position markers around the track and qualitative analysis was performed. During the field tests, there was unintended civilian vehicle traffic traveling on the asphalt road adjacent to the track. The times that these vehicles passed the closest point of approach (CPA) (designated by the pole marker by the road) were documented and logged. In addition to the multitude of interfering vehicles, explosions, and other background noises were present during the test and were documented as well.

The spectrograms in Fig. 7 and Fig. 8 from the balloon array at 512 m elevation (top figure) and the ground array (bottom figure) show a complicated acoustic environment encountered at the test location in August. First, we can see that both arrays can easily detect the propane cannon shots (indicated by the strong vertical lines in the spectrograms). Secondly, it's clear that the elevated balloon array can detect many more acoustic events/sources and over longer periods of time while the ground array can only detect the continuous sources from the intended and unintended vehicles when they are near the CPA. For example at the 29.5 minute mark, the HMMWV was near CPA and the vehicle is clearly detectable. Note that the spectrum of the received signal at the ground array is much broader and higher in intensity due to close proximity while the spectrum of the received signal at the elevated array is not as broad and lower in amplitude because the higher frequency components have been "low-pass" filtered by the atmosphere. However, at lower frequencies, the balloon array was able to detect the idling HMMWV, indicated most prominently by the 50 Hz line at the beginning and the end of the run. As the HMMWV maneuvered around the track, harmonic lines varied with the changing RPM and velocity. A qualitative comparison based on the HMMWV harmonic lines from the spectrograms in Fig. 7, shows at least a factor of two increased in detection range for the balloon array compared to the ground array.

During the same test event, there were two dump trucks (unintended sources) traveling on the asphalt road as indicated in the top figure around the 31st minute in Fig. 7. The varying spectral lines (approximately 5 s apart between vehicles) are due to the gear shifts and RPM changes as these vehicles maneuver and make turns on the asphalt road approximately at 500 m north of CPA and again at 1000 m south of CPA. The varying harmonic frequencies of these dump trucks are detectable for approximately 100 s from the elevated array but only approximately 40 s from the ground array. The longer detection duration by the elevated aerial sensor corresponds to approximately greater than twice the detection range.

4.3. Potential Reflection and Multi-path Problems

Reflections from the ground and other ground structures can be a potential problem for acoustic detection from aerial balloons. Fig. 9 shows amplitude vs. time plot for a propane cannon shot from a stand of trees located south of the track at a distance of the 429 m from the ground array (see Fig. 2 (b)). The "double peak" in the signal from the balloon array is due to reflection. The amplitude and amount of constructive/destructive interference is a function of many factors including the nature of the acoustic source (e.g., transient vs. continuous signal), the relative geometry of the source and receiver (e.g., position of the acoustic source relative to the ground and the nearby surrounding, the angle of fire of the weapon, the elevation of the balloon, the distance from the balloon to the acoustic event) and, clearly, the atmospheric conditions. Reflections might not be a problem if detection of is of primary interest. However, it will definitely cause problems for localization and classification. In this preliminary field experiment, we did not make any attempt to mitigate reflections. Clearly further experiments and analysis are needed to understand and quantify (if possible) the effect of reflections and multi-path observed by acoustic sensors on aerial balloons.

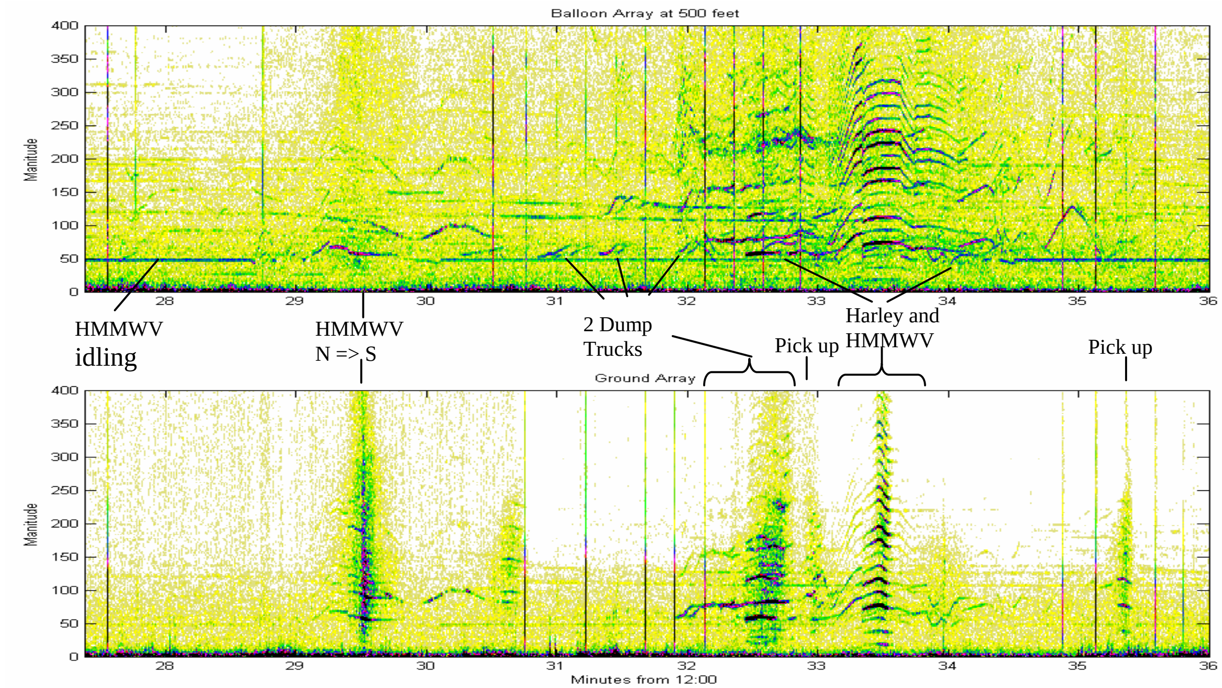


Fig. 7: *Spectrograms from the balloon array at 152 m elevation (top) and ground array (bottom) showing the complicated acoustic environment at the test location. The CPA to the ground array for the various vehicles is labeled. The vertical lines across the spectrogram are impulses from the propane cannon or other transient sources.*

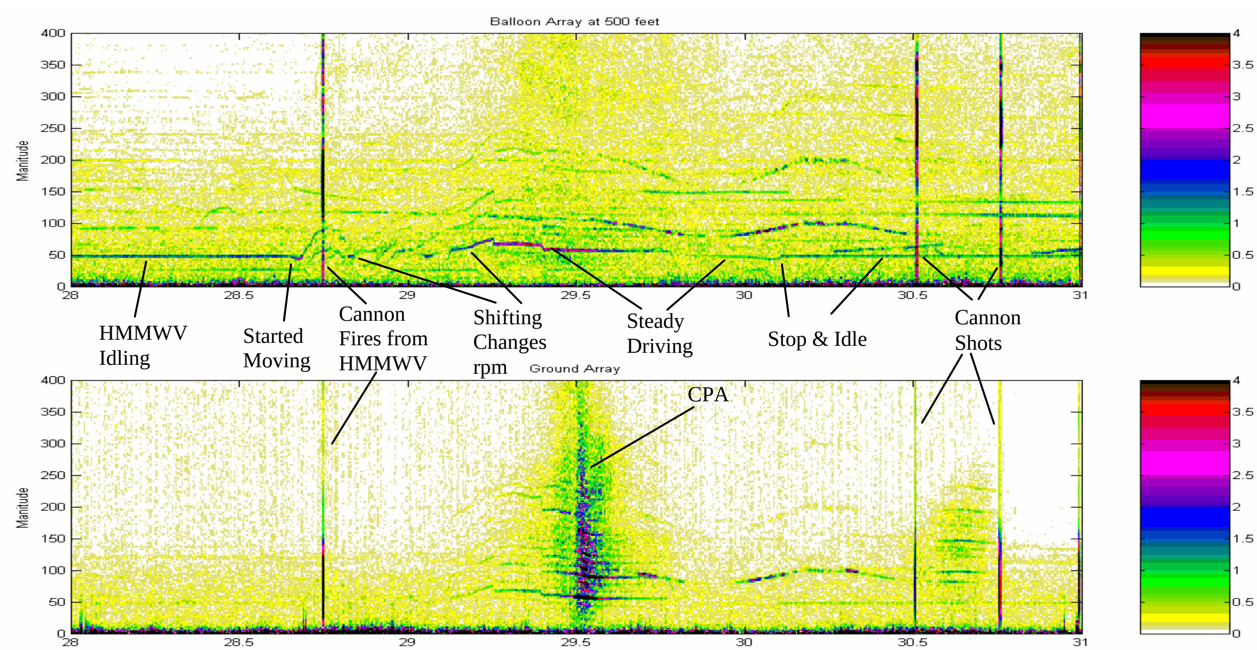


Fig. 8: *A portion of the spectrogram in Fig. 7 that shows the HMMWV driving from the north end of the track to the south end of the track among 3 propane cannon shots. Aerial sensor clearly detects the engine idling at 50 Hz and other engine harmonics at increased signal levels for longer time durations corresponding to longer detection ranges.*

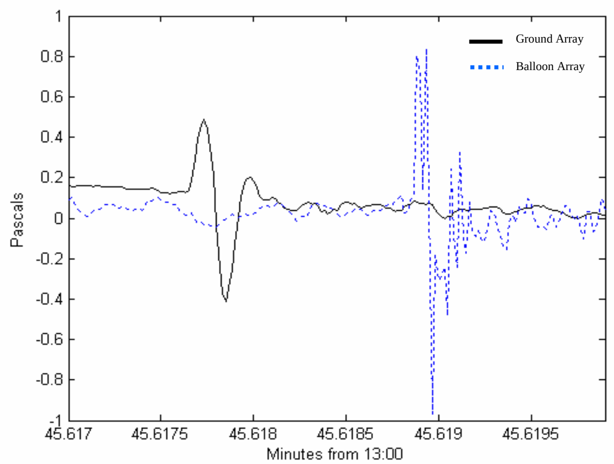


Fig. 9: *Amplitude vs. time plot for a propane cannon shot from a stand of trees located at the 429 m south of CPA (see Fig. 2 (b)). The "double peak" in the signal from the balloon array is due to reflection.*

5. CONCLUSIONS

In this paper, we discuss the motivation and potential advantages of having acoustic sensors on aerial platforms such as balloons shown in Fig. 3. We present data and qualitative results/analysis via signal amplitude, spectral sum and spectrogram plots showing distinct increase in detection capabilities of acoustic sensors on the elevated balloon vs. the ground for acoustic sources at distances greater than 100 m. Specifically, we can see an increase in signal levels of several factors for both impulsive events and continuous sources and increase detection range of at least a factor of two at several elevations up to 152 m. We do observe reflections from the balloon array for some of the propane cannon shots at certain elevations. We discuss the potential problems and the need to investigate them further.

The indication of acoustic performance enhancements due to altitude is an important result of this experiment. The Army is presently pursuing the benefits of airships for elevated sensor deployments. Consequently, the quantitative improvement to acoustic detection and target location due to airship deployment needs to be more fully quantified. The integration of airborne acoustic sensing with distributed ground sensor networks will lead to improved performance with the implication of significantly better battlefield situational awareness. Further experiments at other locations in the US will be planned to include additional sensors and other special operational needs, perhaps during Advanced Warfighting Experiments and exercises at the National Training Center. NVESD and ARL will pursue these opportunities as they occur. The objective of future experimentation will be to develop a table of acoustic range detection and identification as a function of sensor parameters, targets, hostile activity and environmental conditions.

In the near future, we will explore beamforming capabilities and compare experimental detection results to the predicted detection results from ABFA. We will also conduct experiments with larger impulse sources, controlled narrow-band emitters, and higher balloon elevations to allow more precise determination of the effects of elevation on acoustic sensitivity and effects of reflections.

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